VEGETATIVE AND REPRODUCTIVE GROWTH IN DETERMINATE AND INDETERMINATE SOYBEAN INFLUENCED BY CANOPY STRUCTURE

By

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Soybean [Glycine max (L.) Merr.] is known to respond to variation in canopy structure. Numerous studies demonstrated positive yield responses to reduced row widths, whereas other tests failed to show an advantage to narrow rows. Interestingly, most studies showing an advantage were conducted with indeterminate cultivars primarily in the corn-belt states. Studies that did not demonstrate a positive response used determinate cultivars primarily in the southern states. Few tests included both determinate and indeterminate types.

The hypothesis of this study was that determinate and indeterminate soybean cultivars, due to their different growth and reproductive habits would respond differently to canopy structure and that the indeterminate types would be more responsive to dense canopies resulting from narrow rows than determinate types. A series of experiments was conducted in Gainesville, Florida (29°38'N), during 1984 and 1985 to determine the vegetative and reproductive responses of determinate and indeterminate soybean cultivars in various canopy arrangements as created by altering

planting dates and inter- and intra-row spacing, resulting in variable plant density.

Cultivars Kirby (determinate, MG VIII) and Duocrop (indeterminate, MG VII); planting dates, May and July; inter-row spacings, 91, 61, and 30 cm; and intra-row spacings, 8 and 18 cm, were used. Plant densities that resulted from the inter- and intra-row combinations were 6, 9, 14, 18, 21, and 42 plants m^{-2}. The parameters recorded included height, nodes on main stem and branches, branching, branch length, pods on the main stem and branches, leaf area index (LAI), crop growth rate, light interception, and biomass and seed yield. Biweekly samplings were growth-analyzed for these parameters and reported on per plant and per square meter bases.

Plant height, branch length and main stem and branch node numbers were greater in the indeterminate cultivar. Total and seed dry matter accumulation were greater in the determinate cultivar for both planting dates and years. Significant interactions among cultivars, planting dates, and plant densities were observed for LAI and pod number on branches in the May planting and for branch pod numbers on main stem, and seed yield in the July planting. All parameters decreased per plant but increased per square meter for both determinate and indeterminate cultivars with increasing density, except for total branch length and weight. Planting patterns approximating a square arrangement (close-row spacing), significantly increased main stem and branch nodes, branch numbers, main stem and branch pods, CGR and total dry matter and seed yield for both cultivars. Seed yield was optimized for both determinate and indeterminate cultivars by high plant density in close-row spatial arrangements whether seeded at an optimum or a late planting date.

CHAPTER I
INTRODUCTION

Soybean [Glycine max (L.) Merr.] is one of the most important oilseed legumes in the world and its popularity for oil and protein is increasing. Approximately 65% of the world oilseed production is from soybean, and in the United States, it is second only to corn in value. The United States produces nearly 75% of the total world supply, and approximately 50% of the production is exported.

Soybean genotypes are daylength sensitive and therefore, the latitudinal range of adaptation for genotypes is narrow. Soybean is also affected by planting date due to photoperiodic and temperature effects.

Generally, soybean genotypes of maturity groups later than IV are more sensitive to photoperiod, especially long days, than early genotypes. However, genotypes may also differ in photoperiod sensitivity, among specific maturity groups (Boote, 1981). Hartwig (1954) suggested that vegetative period should be 45 days minimum to optimize seed yields.

Soybean exhibits two types of growth habit, determinate and indeterminate. The determinate type terminates the stem in a pod-bearing raceme, while the indeterminate type does not terminate in an inflorescence (Etheridge et al., 1929). Growth habit and photoperiod response generally affect canopy structure, light interception, and potential seed yield. Cultural practices (genotype selection, inter-

and intra-row spacing and time of planting) may need to be tailored to best fit the growth habit and photoperiodically determined stature in order to maximize light interception, total dry matter, and seed production.

Generally, determinate soybeans are grown in wide-row spacings and achieve canopy closure at or near the onset of reproduction, which terminates further vegetative growth. Canopy closure results from numerous branching and overlapping between rows. Most observations indicate that branches contribute more pods and seeds than the main stem in determinate cultivars and that indeterminate types are less prone to pod production on branches. Therefore, the two types may not respond in the same manner to the spatial arrangement. The tendency for indeterminate cultivars to produce more pods near the central axis than on branch terminals could improve their seed yield in closer spacing.

In view of the different growth habits, dates of planting may need to differ for determinate and indeterminate types. Ultimately cultural strategies should be based on growth habit and photoperiod response as related to latitude and seeding date, in order to maximize canopy closure and light-interception. Vegetative and reproductive growth characteristics that influence seed yield should be over-riding considerations in cultural strategy programs.

The investigations reported herewith were initiated to test the hypothesis that determinate and indeterminate soybean cultivars respond differently to canopy structure as follows: 1) indeterminate cultivars of normal stature respond positively to increasing canopy

density, resulting from narrow rows and high plant population, and 2) determinate cultivars do not respond to increasing canopy density. The major objective of this study was to determine the responses of determinate and indeterminate soybean cultivars to varying canopy structures.

CHAPTER II
LITERATURE REVIEW

Soybean has the ability to adjust to space or plant density. Growth habit may be determinate, semi-determinate, and indeterminate type. Genetic and environmental factors including latitude dictate the growth and cultural management of different growth types in different geographical locations. In the United States, northern cultivars are predominantly indeterminate types and are derived primarily from Manchurian and Hokkaido breeding material (Leng, 1973). Southern cultivars generally are determinate types, derived mainly from material from Taiwan or southern China.

Soybean is also capable of compensating for low plant densities by adjustment in one or more yield components, e.g., branching and pods plant^{-1}, seeds pod^{-1} and seed size (Lehman and Lambert, 1960). Thus, yield levels may remain relatively constant over wide ranges of population. However, determinate and indeterminate growth types may respond differently with a given space and density. Management strategies are determined by growth type which also influences productivity (Hinson and Hartwig, 1977).

Determinate and Indeterminate Growth Habit

A determinate soybean type terminates vegetative growth with a pod-bearing raceme, while indeterminate types do not have a terminal inflorescence (Etheridge et al., 1929). Bernard (1972) suggested

that the difference between determinate and indeterminate soybean is a result of the timing of the termination of stem growth and the way in which it terminates. He observed that a determinate type was one in which the stem growth terminated abruptly at the onset of flowering while in the indeterminate type, stem growth, node, and leaf production continued for several weeks after flowering.

It has been postulated that the competition between vegetative and reproductive growth in indeterminate soybean cultivars may be detrimental to yield (Hicks and Pendleton, 1969). If shedding and/or abortion of the reproductive parts of soybean is related to the available photosynthate supply, then simultaneous reproductive and vegetative growth could result in reduced pod set and potential reductions in grain yield.

Hinson and Hartwig (1977) stated that the genotype dt_1dt_1 causes plants to be determinate while Dt_1Dt_1 genes are responsible for indeterminate type. Bernard (1972) described two genes, dt_1 (determinate) and Dt_2 (semi-determinate), controlling stem termination with dt_1 epistatic to Dt_2 or dt_2. He developed isolines of 'Harosoy' and 'Clark' which differed only in stem termination. Studies involving the determinate, semi-determinate, and indeterminate isolines of Clark and Harosoy have shown that both the dt_1 and Dt_2 decreased plant height, number of nodes on the main stem, and maturity. Yields of the semi-determinate were better than or at least equal to, indeterminate isolines, while the determinates yielded equal to or less than the indeterminates.

Indeterminate cultivars generally begin to flower when plants have reached less than half the final plant height whereas determinate cultivars have reached nearly full height before flowering is initiated. Plants with indeterminate growth habits, referred to as semi-determinate types, have a dominate gene Dt_2 that causes gradual termination of stem growth. The common form of the determinate stem type is controlled by dt_1, a recessive gene that abruptly terminates stem growth at the time of flowering (Pickle et al., 1984). Hartung et al. (1981) evaluated near isogenic lines of indeterminate Clark and Harosoy possessing various genes for stem termination and maturity. The substitution of genes, delaying flowering and maturity, as they reported, significantly increased the number of main stem nodes, stem length, lodging, branches plant^{-1}, and seeds plant^{-1} but reduced seed weight. Genes hastening flowering and maturity had the opposite effect. The genes for semi-determinate stem growth (Dt_2) significantly reduced the number of main stem nodes and stem length. The gene for determinate growth (dt_1) significantly reduced the number of main stem nodes and also reduced the stem length and lodging. Although there were fewer three-seed pods on the dt_1 isolines, seed yield was not significantly lower than the indeterminate types. The number of pods borne on the main stem nodes, 15 cm or less from the soil surface, was significantly greater in determinate types than in the indeterminate or semi-determinate types.

Johnson et al. (1960) described determinate cultivars as producing a terminal inflorescence and differentiation of the terminal meristem primordia into simple, sessile, bracteal leaves instead of

compound, stipulate ones. The terminal meristems of indeterminate cultivars on the other hand, continue to produce primordia of compound leaves so long as the meristems remain active. After flowering stops, the terminal bud contains an accumulation of these leaf primordia that do not continue their development. Hicks and Pendleton (1969), when comparing determinate and indeterminate soybean isolines, reported a 4.6% yield increase for the tall determinate types over the normal indeterminate checks. They concluded that a determinate stem may be a desirable characteristic for high yielding cultivars in the north central soybean production areas.

Egli and Leggett (1973) reported that at initial flowering, determinate types had reached 84% of their maximum height compared to 64% for indeterminate types. Although stem elongation of the determinate type was nearly complete when flowering began, it continued to increase in dry weight. The number of nodes produced by indeterminate types in the interval between initial flowering and maturity was an average of six in 2 years. Indeterminate types flowered 14 days earlier than the determinate types. They suggested that the longer period of flowering and pod set for indeterminate types, which would result in more total photosynthate production, may partially compensate for the competition between vegetative and reproductive growth.

Several investigations have been conducted to determine the effects on determinate, semi-determinate, and indeterminate genotypes of altering row spacings and plant populations (Green et al., 1977; Hicks and Pendleton, 1969; Shannon et al., 1971; Wilcox, 1974). The

theory underlying these researches is that the determinate plant type may require different production practices (including different row spacing and/or plant densities) than the indeterminate type. Foley et al. (1986) suggested that the date of planting at a given location may need to be different for a determinate cultivar than for an indeterminate cultivar. They also reported that stem termination type significantly affected maturity, with the determinate lines averaging more than 3 days earlier than the indeterminate lines. Yield did not differ significantly for stem termination when planted in 76-cm row spacing. Plant height was 25.7 cm less in the determinate lines than the indeterminate.

In Taiwan, Thseng (1982) reported that pod number on the main stem was independent of all other characters in determinate crosses, while branch number was similarly independent in indeterminate crosses. In six F7 lines (determinate, indeterminate, and semi-determinate) with 18 nodes on the main stem, branch number, pod number, and seed number plant^{-1} were in the order--indeterminate < semi-determinate < determinate. When node number was fixed, indeterminate types tended to flower earlier and for a longer period than determinate types. However, semi-determinate types were the earliest and gave the highest seed weights and yields.

Shroyer (1981) conducted a series of trials over 2 years on soybeans of indeterminate, semi-determinate, and determinate growth, sown on three dates starting in mid-May at 3 wk intervals in rows in 69, 34, and 17 cm apart, at 33, 63, and 93 plants m^{-2}. He reported that plant height, number of nodes, lodging, seed yield, and height of lowest pod

increased as row spacing decreased from 69 to 34 cm. With a decrease in row spacing, plant height increased to a greater extent in indeterminate cultivars than in the others; whereas determinate cultivars were more affected as population increased. Days to flower, seed yield, and number of nodes at maturity decreased with an increase in lateness of sowing.

In Poland, Federowska (1981) studied the growth and development of 80 soybean cultivars during 1975 to 1978. He described cultivars that were characterized by intensive growth up to the end of flowering, thick green pods located at the top of the main stem and desiccating slowly in the autumn as determinate. Cultivars exhibiting continuous growth before and after flowering were classified as indeterminate types, and indeterminate cultivars exhibiting characteristics of both types were classified as semi-determinate. Determinate cultivars usually exhibited greatest daily growth, and particular vegetative phases were shorter than for indeterminate cultivars. Federowska concluded that climatic conditions had considerable effect on the different growth characteristics and those of the determinate cultivar were best suited to the conditions of central Poland (ca. 52°N). Thseng (1981) reported that vegetative vigor in determinate cultivars was expressed as rapid weight increase, large leaf area, and thin leaves at flowering. Indeterminate cultivars had the first two characters but thick leaves at flowering. Bulakh (1979) observed in Vavilova, USSR, that cultivars with a projecting stem apex tended to be indeterminate while those with a hidden apex were generally determinate. He also reported that in

short days, indeterminate cultivars tended to show determinate habit, especially those of the semi-determinate cultivated type.

Research results indicate that both the determinate and indeterminate types also have different responses to N, evapotranspiration, water use efficiency, and dry matter accumulation. Thseng (1980) reported that a spring application of N to determinate cultivars with high vigor decreased growth and yield, while N application generally increased yields of cultivars with low vigor. Determinate cultivars generally had a higher leaf weight per unit leaf area than indeterminate cultivars. The response of determinate cultivars to N in autumn was generally greater than that of indeterminate cultivars. Yoshida and Gotoh (1975) reported that at early flowering, the determinate cultivar had a higher rate of translocation of ^{14}C assimilates to seeds than indeterminate types. At the age of pod development and more particularly at pod filling, this order was reversed. Bello et al. (1980) found a linear relationship between N accumulation and N_2 fixation. They reported that after pod filling, indeterminate (Williams) fixed more N_2 than the determinate (Elf) counterpart. The determinate cultivar was consistently low in N_2 fixation ability throughout its development. Fixation of N_2 per unit land and for all cultivars was significantly higher at the higher planting density than at the lower density, but this was not reflected in plant N uptake, seed N, and seed yield.

Singh and Whitson (1976) reported that total evapotranspiration in plants of determinate and indeterminate isogenic lines was 39.0 and 41.2 cm and use of available water was 59.6 and 56.4%, respectively.

Differences in evapotranspiration resulting from differences in growth habit were only a small fraction of total evapotranspiration. They also reported that determinate lines yielded 24.9% more seed and used 5.6% more water than did the indeterminate lines. Differences in water use efficiency were more closely related to differences in seed yield than to evapotranspiration.

Beaver and Cooper (1977) reported that indeterminate cultivar Corsoy accumulated more dry matter in reproductive parts than determinate (Elf, Clark, and Williams) types. Branch pod dry weight of the determinate type comprised a greater part of total dry weight than that of the indeterminate cultivars.

In the indeterminate cultivars, percent protein and oil content of the cotyledons and seed coat decreased with decreasing seed size (Thseng, 1976). In a study of six determinate and four indeterminate soybean cultivars, sown at four planting densities and three planting dates, Thseng and Huang (1976) found that height, node, pod, and seed numbers, seed yield, duration of flowering, maturity, and oil content were higher in indeterminate cultivars than the determinate cultivars. Days to flower, protein content, and 100 seed weight were greater in determinate cultivars. Indeterminate cultivars were more adaptable to variation in sowing date. They also reported that yield and yield stability were generally higher in indeterminate than in determinate cultivars. In another study, Thseng and Lee (1976) found that in determinate and indeterminate soybean cultivars sown in autumn, plant height was 74 to 96% and 46 to 65% of early sown plants, respectively, when measured at the beginning of flowering. At the early pod

development stage, vegetative material formed 69 to 78% of the total in determinate cultivars and 43 to 60% in indeterminate cultivars. The determinate type showed vigorous growth early in the season, while growth was more evenly distributed in the indeterminate type. Competition between vegetative and reproductive parts appeared to be greater in indeterminate than determinate cultivars.

Thseng and Hosokawa (1972), at Hokkaido University in Japan, derived an equation to classify soybean cultivars in terms of growth habit, as follows:

$$\text{Growth habit} = [A/(A + B)] \times 100$$

where A = increase in node number after first flowering and B = node number at maturity. The equation was equal to 0 for determinate, less than or equal to 50% for semi-determinate, and 50% for indeterminate cultivars. They also reported that coefficients of variation for seed weight, petiole length, and length of central leaflet were in the order of indeterminate > semi-determinate > determinate. Flowering took place later in determinate types and they had longer first internodes than semi-determinate and determinate types.

From the above discussion, it is observed that growth habits of both the indeterminate and determinate soybeans are genetically controlled. Indeterminate genotypes are characterized by a long, tapering stem with very slender internodes and few pods per node near the stem apex. This phenotype occurs as a result of the terminal bud remaining vegetative during most of the growing season. Indeterminate types which flower earlier than determinate types are commonly grown in the northern United States. The determinate types, on the other

hand, are characterized by a shorter, thicker stem (at maturity) with substantially fewer total nodes and possess a long terminal inflorescence bearing a cluster of many pods. This phenotype results from the apical bud ceasing vegetative growth at the onset of flowering to become a terminal inflorescence. Generally, determinate types are commonly grown in the southern United States.

Spacing and Plant Density

The relationship between crop yield and plant density may be described by two distinct types of growth curves (Holliday, 1960; Gutstein, 1973). In the case of vegetative production, an asymptotic function was obtained with increasing plant density while for the reproductive yield, the relationship was parabolic.

Although the general effect of plant population on yield of soybean is well defined, its interaction with planting pattern (or spatial arrangement) in development of efficient canopy structure, growth, and developmental characteristics, is still not fully understood. Numerous researchers have investigated optimum spacing and population for soybean production. In many experiments reported, seed yield and other agronomic characteristic, responses to plant spacing, and population density have frequently been conflicting. Responses of the determinate- and indeterminate-types of soybean in varying spacing and population is still in question since the two types generally have not been directly compared. Probst (1945), in a 4 year study, planted soybean cultivars (Illini, Mandell, Dunfield, Mukden) in Indiana with intra-row spacings from 2.54 to 12.7 cm and

inter-row spacing of 76.2 cm. He reported that highest yield was obtained when the plants were spaced 5.08 or 7.62 cm apart. He also indicated that thick planting was conducive to lodging and delayed maturity, and had little effect on plant height. Doss and Thurlow (1974), in Alabama, reported that cultivars had the greatest influence on plant height. Final plant heights ranged from 0 to 15 cm greater for 'Bragg' than for 'Hampton 266' in their study. They used two row widths of 60 and 90 cm, and three plant populations, 107,600, 215,300, and 322,900 plants ha^{-1}. They reported that height was increased by irrigation and increased plant density but was not affected by row width. Average seed yields were influenced more by irrigation and cultivar than by row width and plant density in their study.

Weber et al. (1966), using 'Hawkeye' soybeans in Iowa in 12.7, 25.4, 50.8, and 101.6 cm rows with 64, 128, 256, and 512 thousand plants ha^{-1}, reported that highest seed yield occurred in 25.4 cm rows with 256,000 plants ha^{-1}. On the other hand, total dry weight was maximized in 12.7 cm rows with 512,000 plants ha^{-1}, i.e., the higher the population, the higher the total dry matter gain. They claimed that maturity date, plant height, and lodging were relatively unaffected by row width, but these parameters tended to increase at higher plant densities. They also reported that percent protein in seed decreased slightly in the wider rows and with lower populations, while percent oil showed an inverse relationship to protein. At a given population, pod and seed numbers $plant^{-1}$ were maximized at the 25.4 cm row width and consistently decreased with increasing plant population. They observed that as greater plant competition took

place, a decrease in seed yield and an increase in total dry weight occurred at higher densities. Regardless of row width, increased plant density resulted in taller, more sparsely branched plants bearing fewer pods and seeds than at lower densities. It was evident that increased branching was related mainly to the lack of plant competition. Further, it appeared that branching was not a critical factor in maximizing seed yield since the highest yields were obtained at high plant densities, which had relatively low branching frequency. Allessi and Power (1982) expressed a different view. They reported that in North Dakota, under less severe water stress, plant and row spacing had no effect on soybean [maturity group (MG) 0] seed yield, but narrow rows (15 cm) enhanced water use efficiency prior to flowering. Taylor (1980), in Iowa, observed that plants growing in wide rows were taller, had a greater leaf area, set more pods, and weighed more than narrow row plants during July and August in a dry year. The wide row plants had a higher water potential than those in narrow rows but still the wide rows did not yield more seeds than the narrow rows. Ramseur et al. quoted Palmer and Quesenberry who stated "seed yields under irrigation were greater at lower populations than at higher populations" (1984, p. 445); however, the Ramseur et al. (1984) study failed to support their conclusion. They further reported that intra-row spacings up to 45.7 cm had little influence on the yield of cultivar Braxton. Willey and Heath (1969) pointed out that plant population should not only be defined in terms of plants per unit area, but also in terms of the arrangement of plants on the ground.

The closer the arrangement of plants on a given area approaches a uniform distribution, i.e., square arrangement, the greater will be the yield (Wiggans, 1939). Other things being equal, the narrowing of the distance between rows until the distance between rows equals the space between plants in the row, should result in greater yield. There is nothing to be gained by seeding beyond a given optimum planting density. In Georgia, Johnson and Harris (1967) investigated the influence of plant population on yield of four soybean cultivars of MG V through VII. They planted the cultivars in 3 years during May at a 91.44 cm row spacing and a density of 3.3, 6.6, 13.1, 26.2, 39.4, and 52.5 plants m^{-1} of row. They reported that almost all cultivars required 26.2 plants m^{-1} for highest yields. In addition, yield of neither cultivar was significantly reduced by 52.5 plants m^{-1} of row.

Shannon et al. (1971), in Indiana, revealed that competition between the determinate and indeterminate genotypes within each variety (Harosoy and Clark) showed few significant differences for any character. Competitive effects on yield among genotypes diminished as spacing increased and competition was nonexistent at 65 cm or more between hills. Walker and Fioritto (1984) examined eight indeterminate and three determinate cultivars of MG II and III in Ohio in 76 cm rows with 38.9 viable seeds m^{-2} and 19 cm rows with 52.7 viable seeds m^{-2}. They compared parameters such as maturity, mature plant population, seed yield, and apparent harvest index, among which only seed yield showed a significant cultivar and planting pattern interaction. They also reported that several indeterminate and three determinate cultivars showed a high yield response to the narrow-row

planting pattern. An increase of 18% average yield was obtained from decreasing row width from 76 to 19 cm. The apparent harvest indices were similar for determinate and several indeterminate cultivars under study. The treatments used, however, are confounded and row-width effect cannot be separated from an increase in plant density.

Increasing planting densities through closer row spacing at Knoxville, Tennessee, reduced the proportion of seed that was produced on the bottom part of the soybean plant (Parks and Manning, 1980). Most of the seed produced in dense, narrow-row canopies were in the uppermost part. This had an added advantage in that the seeds were produced closer to the photosynthate source. Likewise, the largest seeds produced on determinate type plants were in the upper canopy. Parks et al. (1982) reported that changing plant density within individual rows had no great effect on yield except in very few cases. A significant drop in seed yield was observed with only two plants per 30 cm of row. Row spacing significantly affected yields at all locations in their study using cultivars Essex, Forest, and Mitchell. Yields from 25 cm rows were higher than the other intra-row spacings at all locations and were highest with 5645 and 5712 kg ha^{-1} in two locations. They mentioned that a 202 kg ha^{-1} seed yield increased when row spacing decreased from 101 to 76 cm. A 134 kg ha^{-1} increase occurred when row spacing went from 76 to 50 cm and a 807 kg ha^{-1} increase occurred when row spacing went from 50 to 25 cm. Beuerlein and Ryder (1981) reported from a research study of 54 different production systems in seven different locations in Ohio between 1974 and 1977. When soybeans were planted in the first half of May,

there was a 941 kg ha^{-1} yield increase as rows were narrowed from 101.6 to 17.8 cm. This averages approximately 11 kg ha^{-1} yield increase for each cm the rows are narrowed. Spidle et al. (1980) observed in North Dakota that soybean cultivars (Chippewa-64, Anoka, SRF-100, and Corsoy) yields in a May planting increased approximately 8 kg ha^{-1} with each cm the row spacing decreased from 91.44 to 30.48 cm. In June, planting yields increased about 3 kg ha^{-1} with each cm of row decrease.

Lehman and Lambert (1960) reported that seed yields in Minnesota tended to be higher at a narrow spacing between rows. The effect of spacing within rows was variable. The four components of yield they studied, 100 seed weight, seeds pod^{-1}, seeds $plant^{-1}$, and pods $plant^{-1}$, were affected to some degree by spacing, however, seed and pod numbers were affected more than seed weight and seeds pod^{-1}. The relative importance of branches varied with spacing for seed and pod number but had little or no effect on seed weight and seeds pod^{-1}. Cooper (1977) reported that in Illinois, a planting rate of 37 viable seed m^{-2} was near optimum with row widths of 17, 50, and 75 cm with weed control. A yield advantage of 10 to 20% was obtained from 17 cm rows compared to 50 or 75 cm rows, with both early and full season cultivars (MG II, III, and IV). However, earlier cultivars under irrigation tended to be more responsive to 17 cm rows with yield advantages as much as 30 to 40%.

Akanda et al. (1975) in Florida, reported that seed yields were significantly higher in their study in two seasons when the row width was reduced from 91 to 46 cm. They suggested that closer row spacing

of soybean (MG VII, VIII, and IX) as a second crop in a double cropping system could compensate to some extent for the yield loss due to delayed planting. Lueschen and Hicks (1977) conducted a study in Minnesota to compare the agronomic characteristics of three soybean cultivars, Corsoy, Wells, and Hodgson, at three different plant densities: 171,000, 342,000, and 513,000 plants ha^{-1}. Significant yield increases were obtained in only 1 year as a result of higher plant density. Yields in the other year remained constant across densities. They also reported that plant height and maturity were not affected by plant density. The number of branches, pods, and seeds $plant^{-1}$ decreased linearly as plant density increased.

Increased yield from narrow rows varies with seeding rate and cultivar. The optimum seeding rate has to be ascertained for different row widths and cultivars for maximum yield response. Basnet et al. (1974) found in Kansas that soybean (MG III and IV) yield increased as within row spacing increased in narrow rows and when within row spacing decreased in wider rows, i.e., yield increased with increased plant density. Highest yields were obtained from wider within-row spacing in narrow rows (3341 kg ha^{-1}) and from closer within-row spacing in wider rows (3846 kg ha^{-1}). They expressed that changing row spacing itself had no effect on yield. Yield differences were caused by varying plant spacing as well as planting date. Therefore, as row width is narrowed, within-row spacing should be increased. The space given to each plant is the operative factor rather than planting configurations. They further mentioned that as production of branches and pods on branches were suppressed in close

spacing, between or within rows, it seemed that higher plant density in closer plant spacing more than compensated for more branches in wider spacings. Beatty et al. (1982) reported from a study in Arkansas, that number of branches plant^{-1} increased as the row spacing increased from 18 to 96 cm but not significantly. They planted three cultivars of MG V, VI, and VII. Pods plant^{-1} increased as distance between the rows increased and decreased as planting date was delayed. Ramseur et al. (1984), while studying the distribution pattern of yield components in 'Braxton' (determinate) soybean, found that branches contributed more to pod and seed yield than did main stems, whereas seeds pod^{-1} and weight seed^{-1} were similar on stems and branches. Increases in intra-row spacings increased seed number and yield on branches and decreased pod number, seed number, and yields on main stems. They also reported that seed number, pod number, and yield were maximized in the lower half of the nodes while seeds pod^{-1} and weight seed^{-1} were greatest in the upper nodes. They concluded that the large contribution of lower nodes to yield was due to the large proportion of yield borne on branches produced from lower nodes. Increases in intra-row spacing resulted in greater contribution to yield of the large branches and thus to a greater concentration of yield at lower nodes. Weibold et al. (1981) examined yield distribution for 11 determinate cultivars in MG V through VIII grown in 0.97-m rows at 5-cm spacing. They combined pods from branches with pods from the main stem at the node of origin of the branch. They found that at harvest most pods were in the top one-third of the nodes of the canopy. Similarly, Ramseur et al. (1984) found that

the large contribution to yield by branches originating in the lower half of the plant resulted in more total yield from the lower nodes.

Hodges et al. (1983) reported on a comparison of five determinate cultivars (MG V through VIII) grown in several locations in Mississippi over a 4-year period, with seeding from April 15 through July 1 at 2-week intervals and in 17.8-, 76.2-, and 101.6-cm row widths. They found that 17.8- and 76.2-cm row spacings were generally higher yielding than the 101.6-cm row spacing with a constant density. The greatest differences among the row spacings were for May and June plantings, with the least for April and July plantings, even though these plants were smaller in stature than those of other sowing dates. These findings conflict with the commonly held view that small-stature plants are favored more by close rows than tall plants.

Parks and Manning (1980) in Tennessee, reported that as row spacing was decreased from 91.44 to 45.72 cm the number and weight of soybean seeds produced on the lower lateral branches decreased but the number and weight of seeds produced on the upper fruiting branches of the main stem were not affected. Such a row spacing adjustment, while maintaining the same number of plants per 30 cm of row, increases the number of plants ha^{-1}, should increase yields. Pendleton et al. (1960) in Illinois also found the highest yield in 61-cm rows and lowest in 102-cm. Their results based on 352 plots showed a yield advantage of 15% for 61-cm rows over 102 cm. The effect of row spacings on plant height depended on rainfall. With adequate

moisture, plants in narrow rows tended to be taller than those in wide rows and vice versa under dry conditions.

Wright et al. (1984) reported that highest yields of 'Bragg' usually occurred at 20 plants m^{-1}. Yield and plant height increased and seed weight and stem diameter decreased sharply with increasing population density between 1.5 and 13 plants m^{-1} row, but decreased gradually from 13 to 27 plants m^{-1} row. Smith and Hinson (1969) in Florida, found that row widths of 30 to 91 cm produced essentially equal yields when fertilization rates were the same. They reported that early maturing cultivars planted late in low fertility soil in a dry condition might cause a poor stand; however, in those situations, narrow rows usually produced higher yields. Hinson and Hanson (1962) reported from their competition studies in soybean in Florida, that mature plant height was affected by spacing. Although height of Lee was reduced under severe competition at close spacing, the differences were not significant. They also reported that number of branches varied with spacing and genotypes did not respond equally to spacing. Competition tended to influence number of branches in the same direction as yield. Number of nodes varied with spacings and varietal treatment, but the response of varietal treatments to spacing was constant. The decrease in height with increased spacing was associated with shorter internodes rather than reduced node number.

Ceron-Diaz (1981) in Kansas used one each determinate, semi-determinate, and indeterminate soybean of MG III in an experiment to determine the effect of moisture stress in relation to growth habit. May and June plantings were made in 38- and 76-cm rows at 30 and 60

plants m^{-2} at both spacings. He reported that plant height was in the order of indeterminate cultivar Williams > semi-determinate cultivar Will or determinate cultivar Elf. Seed yields were similar for all three cultivars. Burlamaqui (1976) in Ames, Iowa, conducted his research over a 3-year period with six soybean lines differing in growth habit, canopy type, seed size, and seeds pod^{-1}. He reported that variation in seed yield $plant^{-1}$ was associated most with number of pods, which resulted from variation in number of nodes and number of pods $node^{-1}$, the latter having the greatest effect. Where plants were grown at various row spacings, the number of pods $node^{-1}$ and number of nodes usually changed in opposite directions and were responsible for most of the compensation in yield. Enrichment of the atmosphere with 600 ppm CO_2 increased seed yields by 50%. This was due to increases in pods $node^{-1}$ and number of nodes in indeterminate lines and to increased pod production in a determinate line. He also reported that row spacing had no effect on seed yield. Costa et al. (1980) found that planting soybeans in 27-cm rows vs. more conventional 76-cm rows showed an average seed yield increase of 21% over all years, populations, and cultivars. All cultivars produced higher seed yields in narrow row spacing. The three early cultivars (MG 0) generally exhibited a greater yield response (+27%) to narrow-row spacings than did cultivars in maturity groups I and II (+19%). However, the late maturing cultivar generally produced the highest yields over all row spacings, plant populations, and year but responded less to narrow rows. Varying the intra-row plant spacing did not significantly affect seed yields. Increasing plant

populations decreased the number of branches plant^{-1} and increased lodging, seed weight, and LAI.

Safo-Kantanka et al. (1980) studied the effect of row spacing and rectangularity with variable plant density on soybean yield and other components in Canada. Using plant densities ranging from 110,000 to 4,000,000 plants ha^{-1}, they demonstrated significant yield differences by narrowing row width but not by changing rectangularity. In the second experiment they fixed the plant density to 670,000 plants ha^{-1} and row widths were 15, 30, 45, and 60 cm apart compared to previous 10, 15, 20, and 30 cm. The change in row widths in the second experiment resulted in respective rectangularities of 1:1.5, 1:6, 1:13.6, and 1:24. However, the second experiment results indicated that neither seed yield or its components showed any significant response to row spacing. They concluded that changes in inter-row width are more critical to soybean yield than changes in plant arrangement.

From the above studies on effects on spatial arrangement on soybean seed yield, although results are variable, it can be summarized that optimum or high plant density, reduced row width from the conventional 91 or 76 cm to narrow widths generally increased seed yield. Responses of determinate and indeterminate soybean genotypes to varying planting arrangements are conflicting. Generally, the plant height increased with increasing plant population and greater seed yield was produced from the upper canopy of the determinate type. For indeterminate types, it was from the lower half of the plant. Except for seed yield, most parameters were reported on a plant^{-1}

basis rather than land area basis, so no conclusions can be drawn on the latter basis.

Canopy Structure and Light Interception

Canopy closure may be defined as little or no incoming radiation directly reaching the soil surface below the canopy or when few, if any, sunspots are visible on the soil surface around noon on a clear sunny day. The canopy density is usually defined in terms of leaf area index (LAI) which is the total area of one surface of leaves per unit area of land occupied by the crop. As the LAI continues to increase, a stage is reached at which the upper leaves begin shading the lower leaves and competition for light ensues (Watson, 1956).

Soybeans are practically responsive to quality and quantity of sunlight. Light greatly influences the morphological development of the soybean plant by affecting plant height, lodging, branching, leaf area, time of flowering, and maturity. Weber et al. (1966) reported that total dry weight production was highly correlated to LAI. High plant density and narrow row spacing are considered to be necessary for rapid attainment of high LAI. Shibles and Weber (1964) directly related leaf area development to solar radiation interception. Maximum seed yields generally occurred at less than maximum LAI values. Sakamoto and Shaw (1967) concluded that 90% of the incoming solar radiation was intercepted by leaves near the top of a fully developed soybean canopy. Parks et al. (1973) reported that, out of the small amount of radiation penetrating the canopy, less than 10% of the incoming radiation reaches as far as 25 to 30 cm within the plant

canopy. Egli et al. (1970) found the photosynthetic rate of soybean canopy to be almost directly proportional to the percentage of full sunlight. Thus a canopy receiving 50% full sunlight would operate at above 50% capacity. Less than 2% of the total incoming radiation reached the soil surface. A soybean canopy shades the surface soil and may reduce moisture loss through evaporation and increase water use efficiency. Normally losses from deeper horizons are more operative in the water balance of field grown plants. Weil and Ohlrogge (1976) found interaction between canopy level and plant density during the pod-filling period. This interaction might have been, as they reasoned, due to an alteration in the pattern of translocation and an inability of the lowest leaves to respond to increased light intensity.

Determinate-type soybeans grown mostly in wide row-space configurations normally do not achieve complete canopy coverage until the onset of reproductive growth. Canopy closure generally occurs as the result of numerous first order branches. Similar results may not occur for indeterminate cultivars in similar configurations as they are characteristically less prone to branching (Sojka and Parsons, 1983). Therefore, an assumption that more effective canopy closure and light interception might be better achieved in indeterminate cultivars by narrowing row spacing seems reasonable.

Parks et al. (1982) reported that Forest and Essex canopies closed in 70 days, 72 to 90 days, and 85 to 93 days in 51-, 76-, and 102-cm rows, respectively. Wide-row soybeans took about a month longer than narrow rows to complete closure at a given population

density. Forming a complete canopy as soon after planting as possible reduces the need for weed control, surface soil water loss through evaporation, and harvest loss by forcing the soybean plant to form pods higher on the stem. It also protects nodules from excessively high temperatures. All of these factors probably combine to contribute to the higher yields generally obtained in narrow rows.

Duncan (1971) reported that LAI that might be expected for a crop would be modified by cultivar, climate, and management practices. Light interception and canopy photosynthesis depend largely on foliage density and percent ground cover. Brougham (1958) defined critical LAI as that leaf area required to intercept 95% of solar radiation at solar noon. This value for soybean is approximately 3.2 (Pendleton et al., 1960). The irradiance profile in the plant canopy is reported to follow Beer's Law (Monsi and Saeki, 1953),

$$I/I_o = e^{-K}$$

where I = radiant energy received at the bottom of an increment LAI, I_o = incident energy at the canopy top, and K = extinction coefficient characteristic of the canopy. Sakamoto and Shaw (1967) demonstrated by using the above equation that light interception occurred primarily at the periphery of the soybean canopy. When the open space between rows closed, interception was primarily at the top of the canopy.

Shibles and Weber (1964) reported that the amount of dry matter produced depended on light interception and efficiency of utilization. The efficiency of light utilization is conditioned by environmental factors such as water, CO_2, inorganic nutrients, and plant factors such as partitioning and respiration. Another important condition is

the distribution of solar radiation over the leaf surfaces of the crop community.

Dry matter production in equidistantly spaced soybean is a linear function of solar radiation interception. As growth progresses, increasing leaf area development results in increasing percent solar radiation interception which in turn results in an increasing rate of dry matter production. Shibles and Weber (1966) studied solar radiation interception and dry matter production of soybeans grown in planting patterns of 64, 128, 257, and 516 thousand plants ha^{-1} within 13-, 26-, 52-, and 104-cm row spacing. They found that when soybeans were grown in a narrow-row plant arrangement, row width and plant spacing was of little significance in solar radiation interception. Wider spacings (104-cm row) resulted in less interception at any stage of growth and considerably delayed maximum interception.

The above reports show that high plant populations and close spacing are necessary for rapid canopy closure to intercept light efficiently. Determinate cultivars which normally are grown in wide-row spacings generally do not achieve complete canopy closure until the beginning of flowering (R1 stage). Closer spacing can increase the rapid LAI accumulation. Planting densely enough to intercept all the light, resulting in more vegetative dry matter $plant^{-1}$ at the beginning of the reproductive period, should attain greater seed yield per unit area.

Planting Date

Climatic adaptation of soybeans is much influenced by daylength (Johnson et al., 1960). The photoperiodic response of a genotype is a significant factor in determining its adaptation to a particular geographic area (Garner and Allard, 1920). Date of planting for soybean results in a direct effect of daylength. The maturity groups from 00 to III are thought to be relatively tolerant to long days while cultivars in IV to VIII MG required short days for fruiting (Boote, 1981; Huxley and Summerfield, 1974; Johnson et al., 1960; Lawn and Byth, 1973). Yield of soybean decreases with the lateness of planting (Burlison et al., 1940; Henson and Carr, 1948; Hutcheson, 1942; Nelson, 1954). Generally, due to reduced plant stature, late planted soybean should be grown in narrow rows to get higher yield (Akanda et al., 1975; Cooper and Lambert, 1965; Smith and Hinson, 1969). Late planting (later than 15 June) in double cropping systems is a common practice among soybean growers in the southeastern United States (Goli and Weaver, 1986). Camper and Smith (1958) reported that season and date of planting had appreciably more effect on seed yields but it faced more hazards such as insufficient soil moisture, pests and disease etc., than early June plantings.

Boerma and Ashley (1982) studied irrigation, row spacing and genotype effects on late and ultra-late planted soybeans in Georgia. They compared Bragg (determinate) and 'GA 76-32' and 'GA 76-18' (both indeterminate) soybean genotypes in 51- and 91-cm row widths planted in late June or early July (late) and late July and early August (ultra-late). They reported that genotypes did not differ in seed

yield in late planting although 51-cm rows averaged 17% higher seed yield than 91-cm rows when averaged over years and other factors. Indeterminate lines have shown yield increases of at least 4% over Bragg (MG VII) and other determinate cultivars when planted after 20 June.

Nelson and Roberts (1962) reported that the highest soybean yields were obtained in Washington state from the May-5 planting, and the lowest from the June-9 planting. They received the highest yield from 2.5 cm plant spacing in the row. Plant height decreased with increased plant spacing in the row and with delayed planting from 6 to 27 May. Boote (1981) reported that in Florida, March plantings mature by late June and could be double cropped to soybeans (i.e., soybean after soybean).

Hodges et al. (1983), in Mississippi, reported that the average of about 15% reduction in yield in mid-April plantings compared to May (optimum) plantings. In contrast, mid- to late-June planting had an average yield reduction of 33%. They also reported that each day of delay in planting in 76 cm rows after June 10 resulted in a yield decrease of about 47 kg ha^{-1} day^{-1}. Board and Hall (1985) reported that yield losses at nonoptimal planting dates caused by premature flowering induced by short days can be avoided by planting cultivars having a long vegetative period under short days. They also reported that yield losses from a mid-June planting date resulted from reduced branch numbers, which caused a reduction in branch yields. Yield losses can be avoided by increasing branch number $area^{-1}$ by planting in narrow row widths at higher seeding rates. Bello et al. (1980)

reported that the effect of plant population was not evident in increasing total plant N uptake, seed N, or seed yield. The early planting date favored N_2 fixation by allowing a longer period of active fixation but showed advantage in seed yield or total N accumulation. In their study they used 12 planting dates through May and June with two row spacings--38 and 76 cm--and two plant populations--580,000 and 760,000 plants ha^{-1}.

It could be summarized that date of planting has a significant effect on the soybean seed yield. Very early and late compared to optimum planting date significantly reduce seed yield. The effect is primarily due to photoperiod. Yield losses from the late planting could be compensated partially by planting in narrow rows with high plant densities.

CHAPTER III
VEGETATIVE AND REPRODUCTIVE GROWTH OF DETERMINATE AND INDETERMINATE SOYBEAN INFLUENCED BY PLANTING PATTERN, DENSITY, AND DATE

Introduction

Soybean [*Glycine max* (L.) Merr.] cultivars normally are determinate (DT) or indeterminate (INDT) in reproductive types, which may influence their response to the environment and cultural practices. The INDT types maintain vegetative growth from the terminal bud after flowers have initiated at basal nodes, whereas, DT types end vegetative growth by flower initiation in the apical buds (Bernard, 1972; Hinson and Hartwig, 1977; Hartung et al., 1981). Generally, flowering progresses in INDT acropetally and in DT basipetally. At maturity INDT cultivars are observed to have a somewhat inverted conical plant geometry with few pods produced at the upper nodes in contrast to a bushy development and prolific pod production at upper nodes in DT cultivars. Johnson et al. (1982) suggested that this diversity of growth and development habit affects canopy structure likely determines responses to row width.

Soybean seed yields in upper latitudes of the U.S. (> 35°N) have shown a marked positive response to row widths that are less than conventional (76 to 100 cm) (Probst, 1945; Weber et al., 1966; Shibles and Weber, 1966; Cooper, 1977; Gardner, 1978; Parks et al., 1982). Using maturity group (MG) I to IV cultivars in Iowa, Shibles and Weber (1966) obtained the highest seed yields from row width from 25 to 51

cm compared to the conventional. Cooper (1977) obtained similar results at several test locations using MG II and III cultivars, in Illinois. A plant density of 37 plants m^{-2} was optimum irrespective of planting pattern. Gardner (1978) over a 5-year period observed a 12 to 14% yield advantage from 18-cm rows compared to 90 cm with 'Corsoy' and 'Williams' (MG III), at plant densities of 18, 37, and 56 plants m^{-2}. Beuerlein and Ryder (1981) reported that soybean (MG III) seed yield increased 11 kg ha^{-1} per 1 cm decrement in row width from the conventional width. The results cited above are from studies conducted in the cornbelt states, using INDT, and relatively early-maturing cultivars (MG I to III).

Late-maturing, DT (MG V to VIII), which are used predominately in southern latitudes, frequently did not show a positive response to narrow-row widths (Hartwig, 1957; Smith, 1968; Smith and Hinson, 1969; Parks et al., 1982). In fact, Hartwig (1957) in Mississippi noted that there is little or no advantage in row widths less than the conventional (91 cm) with adapted cultivars (DT). However, Hodges et al. (1983), Walker and Fioritto (1984), and Board and Hall (1985) in southern states obtained a yield advantage from narrow rows with DT cultivars (MG VI to VIII).

Johnson et al. (1982) offered an explanation for the apparent disparity of results obtained in northern and southern locations from spatial arrangement studies. They reasoned that row width or plant density were usually not limiting factors, since completeness of canopy closure at the onset of fruiting is the most important consideration, which is usually achieved with late-maturing, DT

cultivars used in southern states. Cultivars that benefit most from narrow rows, flower early and often do not cover the row centers at fruiting. For this reason, late-planted or double-cropped soybean is usually more responsive to narrow rows (Akanda et al., 1975; Boote, 1981; Board and Hall, 1985).

Yield of soybean normally decreases with lateness of plantings (Burlison et al., 1940; Henson and Carr, 1948; Nelson and Roberts, 1962; Cooper, 1971; Board and Hall, 1985). Each day of delay in planting in 76-cm rows after 10 June in Mississippi, yield has decreased about 47 kg ha^{-1} day^{-1} (Hodges et al., 1983).

The primary loci of pod production may vary between DT and INDT cultivars. Ramseur et al. (1984) reported that DT genotypes produced more pods on branches than on the main stem. Parvez and Gardner (1987) also observed more branches and pods on branches in DT, 'Kirby', compared to the INDT, 'Improved Pelican'. Contrary-wise, Thseng (1982) found in Taiwan that branch pod and seed number $plant^{-1}$ were greater in INDT than in DT cultivars.

While much of the experimental evidence to date appears to indicate a differential response of DT and INDT cultivars to spatial arrangement, few studies have directly compared the two types of similar maturity. Therefore, this study was conducted to assess the vegetative and reproductive growth and development responses of DT and INDT cultivars of similar maturity to planting pattern, density, and date.

Materials and Methods

The study was carried out in Gainesville, Florida (29°38'N) in 1984 and 1985 in a well-drained Jonesville Texajunct soil (loamy, mixed, thermic Arenic Hapludalt). Temperature, rainfall, and solar radiation fluxes collected from the nearby Agronomy Meteorological Station (0.6 km from the experiment site) are given in Table 1.

Two soybean cv., Kirby [MG VIII (DT)] and Duocrop [MG VII (INDT)] and two planting dates, 21 May and 8 July, 1984, and 10 May and 2 July, 1985 were used. The six spatial arrangements were derived from three inter-row spacings, 91, 61, and 30 cm and two intra-row spacings, 8 and 18 cm. These arrangements provided densities of 6, 9, 14, 18, 21, and 42 plants m^{-2}. The experimental design was a randomized complete block with four replications.

The plot size was 9 m long and 3 m wide. The 91-, 61-, and 30-cm inter-row spacing treatments consisted of 4, 6, and 8 rows, per plot, respectively, so that two rows bordered the two sample rows in 91- and 61-cm plots and four rows bordered the 30-cm row plots. Fertilizer of 0-22-62 kg (N-P-K) ha^{-1} was applied at seedbed preparation, which included mold-board plowing, tandom disking, and herbicide incorporation with a rolling cultivator. Seeds were treated with Captan (cis-N-((Trichloromethyl)thio)-4 cyclohexene-1,2-dicarboximide) prior to seeding and inoculated with Bradyrhizobium japonicum in a commercial slurry at seeding. Rows were over-seeded and thinned at 14 days after planting (DAP) to one plant per hill for the appropriate intra-row spacing of 8 and 18 cm. Overhead sprinkler irrigation

Table 1. Average monthly temperature, rainfall and solar radiation during the study period (May to December) of 1984 and 1985.

Month	Year	Maximum temperature	Minimum temperature	Rainfall	Solar radiation
		°C	°C	mm	mol m^{-2} day^{-1}
May	1984	31.02	17.51	175.77	40.03
	1985	31.75	17.45	87.12	43.40
June	1984	32.91	20.13	73.15	39.52
	1985	33.58	21.91	164.08	43.31
July	1984	32.35	21.07	207.01	28.83
	1985	32.80	21.41	136.91	40.56
Aug.	1984	33.30	21.57	85.34	35.81
	1985	31.97	22.07	341.12	33.72
Sept.	1984	31.41	19.85	60.96	30.35
	1985	30.86	20.57	83.57	37.58
Oct.	1984	30.02	17.62	45.47	21.66
	1985	30.19	19.57	110.24	30.40
Nov.	1984	23.02	9.79	72.64	14.80
	1985	26.91	16.23	83.82	24.18
Dec.	1984	24.57	10.79	11.18	18.57
	1985	19.96	5.23	29.13	21.46

Source: Agronomy Farm Meteorological Weather Station, University of Florida, Gainesville.

was applied to facilitate uniform germination and to prevent moisture stress during the growing season.

Metolachlor (2-chloro-N(2-ethyl-6-methylphenyl)-N(2-methoxy-1-methylethyl) acetamide), a pre-emergent herbicide was applied 14 days before planting. Additional weed control was done manually as needed. In 1984, lesser cornstalk borer (Elasmopalpus lignosellus Zeller) was a serious problem. Carbofuran (2,3-Dihydro-2,2-dimethyl-7 benzofuranyl methylcarbamate) was applied broadcast after emergence, which resulted in damage to the younger leaves. In 1985, Chlorpyrifos (O,O-Diethyl O-(3,5,6-trichloro-2-Pyridyl)-phosphoro thioate) was applied to control lesser cornstalk borer. Acephate (O-S-Dimethyl acetylphosphoramide thioate) was applied as needed to control the three-cornered alfalfa hopper (Spissistilus festinas Say) infestation.

Plots were sampled and plant components were separated for growth analysis at 2-week intervals beginning 20 DAP until ca. 120 DAP and 96 DAP for both May and July plantings, respectively, in 1984 and 1985. At each sampling, seven plants from the 18-cm and 14 plants from the 8-cm spacing were cut just above the ground in each plot. Sampling began at one end of the plot and systematically moved to the other end of the bordered plot, leaving one border plant between sampling sites. From the seven or 14 plants harvested, a representative plant was selected and separated into its component parts. Parameters measured were plant height, leaf area index (LAI), branch number and total branch length, node and pod numbers on the main stem and branches, and seed and total dry matter (TDM) yields. These were dried to constant weight in a forced-draft oven at 60°C and weighed. Leaf area (one

side) was determined by automatic photoelectric leaf area meter (LI-COR Inc., Model 3100). Leaf area index (LAI) was calculated by the equation: LAI = TDM x leaf fraction x specific leaf area, where TDM is on a land area basis. Light interception above and below the canopy was measured at or near solar noon in each plot in 1985 with a line quantum sensor (LI-COR, Model 191SB) connected to an integrating light meter (LI-COR, Model 188) at 58, 72, and 86 DAP in May planting and at 39, 53, and 67 DAP in July planting. Parameters were also fitted to squareness of planting pattern, defined here as intra-row to inter-row spacing ratio (where 1.0 = perfect square).

Statistical analysis was according to Statistical Analysis System (SAS Institute, 1979). Differences among treatments were tested by analysis of variance (ANOVA), and compared using Duncan's Multiple Range Test (DMRT) at the 0.05 level of significance. In the absence of significant year x treatment interaction, data were analyzed by combining the two years. Parameters recorded from the final sampling (R7) were plotted on a per plant basis by fitting to an exponential model, whereas those on a m^{-2} were fitted by use of linear regression model.

Results and Discussion

Vegetative Growth

Plant height

Mean plant height for the two years was approximately 40% less for Kirby (DT) than Duocrop (INDT) and approximately 40% less for the July than the May planting (Fig. 1a, b; Table 2). Plant height

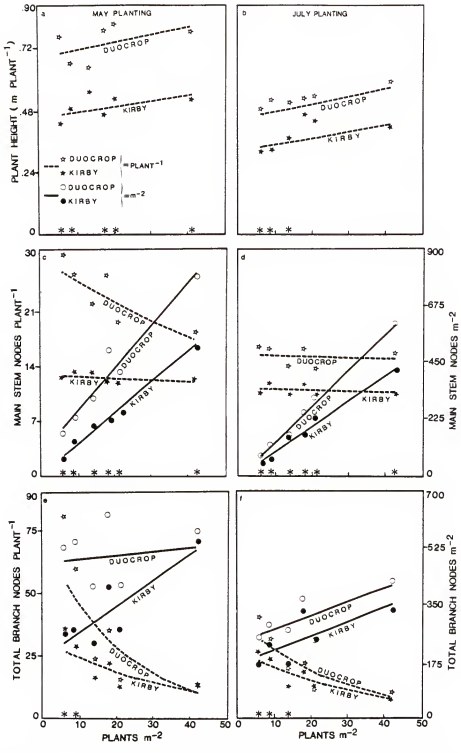

Fig. 1. Plant height, main stem and branch node numbers in Kirby (determinate) and Duocrop (indeterminate) soybean cultivars influenced by density (function of inter- and intra-row spacings) and planting date (average of 1985 and 1986).
*Indicates significant differences between cultivars at each level of plant density ($P < 0.05$) according to Duncan's Multiple Range Test (DMRT).

Table 2. Exponential and regression equations with corresponding r^2 values for several parameters plant^{-1} and m^{-2} in May and July plantings (average of 1984 and 1985 experiments).

Parameters plant^{-1}	Cultivar	May planting Equation	r^2	July planting Equation	r^2
Plant height	Duocrop	$Y=69.94e^{0.003x}$	0.38*	$Y=46.03e^{-0.005x}$	0.27*
	Kirby	$Y=46.12e^{0.004x}$	0.34*	$Y=33.44e^{-0.006x}$	0.17*
Main stem nodes	Duocrop	$Y=27.83e^{-0.011x}$	0.35**	$Y=15.81e^{-0.001x}$	0.25*
	Kirby	$Y=13.0e^{-0.001x}$	0.36*	$Y=11.11e^{-0.0006x}$	0.15*
Total branch nodes	Duocrop	$Y=71.46e^{-0.046x}$	0.51**	$Y=39.23e^{-0.036x}$	0.62**
	Kirby	$Y=31.08e^{-0.025x}$	0.36**	$Y=27.31e^{-0.030x}$	0.47**
Total branch number	Duocrop	$Y=8.70e^{-0.024x}$	0.47**	$Y=8.78e^{-0.023x}$	0.35**
	Kirby	$Y=10.31e^{-0.021x}$	0.35**	$Y=7.62e^{-0.018x}$	0.34**
Total branch length	Duocrop	$Y=294.92e^{-0.036x}$	0.40**	$Y=120.09e^{-0.031x}$	0.26*
	Kirby	$Y=181.79e^{-0.032x}$	0.34**	$Y=91.52e^{-0.026x}$	0.18*
Total dry matter	Duocrop	$Y=75.82e^{-0.032x}$	0.37**	$Y=45.70e^{-030x}$	0.37**
	Kirby	$Y=125.07e^{-0.042x}$	0.57**	$Y=60.38e^{-0.033x}$	0.53**
Stem dry weight	Duocrop	$Y=4.75e^{-0.007x}$	0.25*	$Y=2.92e^{-0.021x}$	0.21*
	Kirby	$Y=16.49e^{-0.027x}$	0.36**	$Y=4.36e^{-0.018x}$	0.35**
Branch dry weight	Duocrop	$Y=17.49e^{-0.044x}$	0.41**	$Y=4.75e^{-0.024x}$	0.22*
	Kirby	$Y=41.32e^{-0.059x}$	0.65**	$Y=8.63e^{-0.032x}$	0.30*
Main stem pods	Duocrop	$Y=24.99e^{-0.015x}$	0.30**	$Y=31.27e^{-0.023x}$	0.27*
	Kirby	$Y=41.34e^{-0.020x}$	0.31**	$Y=25.96e^{-0.013x}$	0.23*
Total branch pods	Duocrop	$Y=66.65e^{-0.037x}$	0.35**	$Y=54.00e^{-0.041x}$	0.42**
	Kirby	$Y=160.65e^{-0.054x}$	0.65**	$Y=63.47e^{-0.037x}$	0.49**

*Significant at $P<0.05$.
**Significant at $P<0.01$.

Table 2.—continued.

Parameters m	Cultivar	May planting Equation	r^2	July planting Equation	r^2
Main stem nodes	Duocrop	Y=91.26+17.13x	0.82**	Y=0.53+13.94x	0.91**
	Kirby	Y=8.71+12.36x	0.95**	Y=3.44+10.08x	0.97**
Total branch nodes	Duocrop	Y=479.79+1.22x	0.68*	Y=232.08+4.17x	0.64*
	Kirby	Y=184.36+8.10x	0.58*	Y=166.25+4.43x	0.53*
Total branch number	Duocrop	Y=43.45+1.97x	0.61*	Y=47.03+1.82x	0.65**
	Kirby	Y=55.15+2.71x	0.54**	Y=34.88+2.18x	0.63**
Total dry matter	Duocrop	Y=500.94+12.09x	0.60**	Y=277.08+9.62x	0.59**
	Kirby	Y=819.85+7.08x	0.59*	Y=366.44+10.02x	0.67**
Stem dry weight	Duocrop	Y=0.08+4.56x	0.59**	Y=10.82+1.29x	0.59*
	Kirby	Y=100.44+4.17x	0.30*	Y=18.54+1.99x	0.60**
Branch dry weight	Duocrop	Y=137.34-0.91x	0.20*	Y=29.37+0.42x	0.30*
	Kirby	Y=288.28-3.71x	0.15*	Y=60.03+0.52x	0.35*
LAI	Duocrop	Y=0.52+0.09x	0.86**	Y=1.52+0.06x	0.68**
	Kirby	Y=1.22+0.04x	0.62**	Y=1.81+0.05x	0.70**
Main stem pods	Duocrop	Y=124.48+12.44x	0.70**	Y=178.32+9.19x	0.59*
	Kirby	Y=206.23+114.99x	0.66**	Y=105.38+13.81x	0.77*
Total branch pods	Duocrop	Y=435.67+7.75x	0.65*	Y=361.87+3.32x	0.59*
	Kirby	Y=1087.22-8.47x	0.45*	Y=412.32+6.19x	0.49*
Seed yield	Duocrop	Y=117.70+3.72x	0.74**	Y=99.59+4.60x	0.68**
	Kirby	Y=239.57+2.35x	0.69**	Y=10.52+1.34x	0.60**

*Significant at P<0.05.
**Significant at P<0.01.

increased slightly with increasing plant density in both dates, which agrees with the results obtained by Weber et al. (1966) and Shroyer (1981). The decrease in plant height in the July planting should be expected, considering photoperiod effect.

Plant height was not influenced by the squareness of the planting pattern (Fig. 2a, b), in either May or July planting. Plant height of Duocrop increased slightly ($P > 0.05$) with increasing squareness in May planting. A positive correlation was observed between plant height and main stem node number (Table 3).

Node development

Duocrop (INDT) developed significantly more nodes plant^{-1} and m^{-2} than Kirby (DT) on both main stem and branches and in both May and July planting dates (Fig. 1c, d, e, f; Table 2). For both cultivars and planting dates main-stem and branch nodes plant^{-1} decreased and increased significantly on a m^{-2} basis with increasing plant density irrespective of planting pattern. Differences between cultivars in branch nodes plant^{-1} and m^{-2} were significant only at the lower plant densities. Kirby gained nodes m^{-2} more rapidly on branches with increasing density in the May planting than Duocrop (Fig. 1e). The effect of delayed planting on reduction of node development agrees with that reported by Board and Settimi (1986) and Parvez and Gardner (1987).

Node number on the main stem tended not to be affected by the squareness of planting pattern (Fig. 2a, b). However, the branch

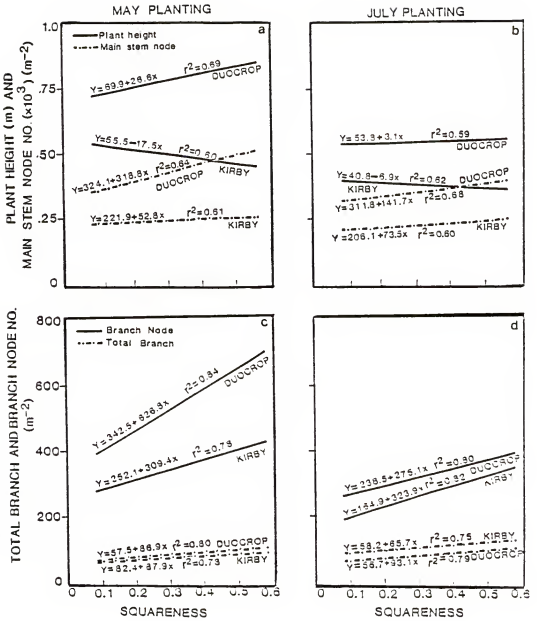

Fig. 2. Plant height, branch number, main stem and branch node number of Kirby (determinate) and Duocrop (indeterminate) soybean cultivars influenced by squareness of planting pattern and dates (average of 1984 and 1985).

Table 3. Correlation coefficient (r) among seed yield and other yield influencing characters in the May and July plantings, 1984 and 1985.

Characters compared	1984		1985	
	May	July	May	July
Plant height vs. main stem nodes	0.70**	0.69**	0.66**	0.79**
Main stem nodes vs. main stem pods	0.82**	0.94**	0.69**	0.79**
Branch nodes vs. branch pods	0.52**	0.67**	0.21NS	0.78**
Total nodes vs. seed yield	0.71**	0.69**	0.61**	0.39**
Total pods vs. seed yield	0.72**	0.80**	0.34**	0.53**
Total branch no. vs. seed yield	0.70**	0.72**	0.31NS	0.42*
Total branch no vs. branch pods	0.45*	0.70**	0.36*	0.73**
Total dry matter vs. seed yield	0.63**	0.78**	0.51**	0.72**

**, * = Significant at 0.001 and 0.01 level.

NS = Not significant.

node number in both cultivars increased significantly ($P < 0.05$) with increasing squareness in both the May and July planting dates (Fig. 2c, d). Pod and seed yield were significantly correlated with total nodes, main-stem nodes, and branch nodes (Table 3).

Branching

Number of branches plant^{-1} and m^{-2} decreased exponentially and increased linearly, respectively, with increasing plant density to the maximum 42 plants m^{-2} in both May and July planting (Fig. 3a, b; Table 2). In the May planting, branch number for Kirby (DT) was consistently greater, though significant only at 21 plants m^{-2}, than for Duocrop (INDT), which agrees with our previous report that Kirby is more prolific in branch productivity (Parvez and Gardner, 1987). The cultivars did not differ in the July planting, but the trends were similar to those in May. Significant cultivar x planting date x plant density interactions were present in the July planting, which resulted from Kirby producing more branches than Duocrop with the increasing density. Total branch length decreased exponentially with increasing plant density in both cultivars (Fig. 3c, d; Table 2) but differences between cultivars were not significant.

Total branch number showed a positive relationship to increasing squareness of planting pattern ($r^2 > 0.75$) in both the May and July plantings for both cultivars (Fig. 2c, d). A significant correlation occurred between total branches and total branch pods. However, the relationship was stronger in July than in May planting

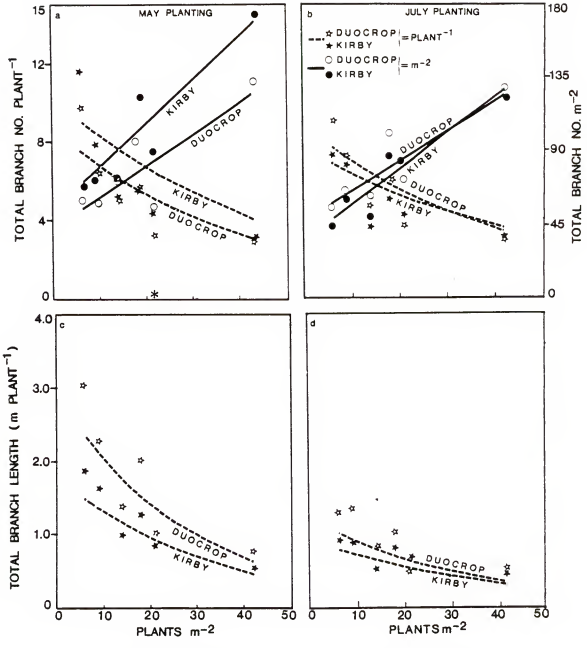

Fig. 3. Total branch length and number in Kirby (determinate) and Duocrop (indeterminate) soybean cultivars influenced by plant density (function of inter- and intra-row spacing) and planting dates (average of 1984 and 1985).
*Indicates significant differences between cultivars at each level of plant density ($P < 0.05$) according to Duncan's Multiple Range Test (DMRT).

(Table 3), meaning the prolifacy of branch-pod production was greater in July than in May planting.

Leaf area index

Leaf area index peaked at 4.8 in the May planting in 1985 and at 1.8 and 4.2 in the July plantings in 1984 and 1985, respectively (Figs. 4a, b, and 5b). In both years and planting dates LAI peaked between 60 and 65 DAP (Fig. 5b). In most cases Kirby (DT) had a higher LAI than Duocrop (INDT). The lower value of LAI in July 1984 compared to 1985, was attributed primarily to later planting in 1984, nematode damage, and soil compaction. Also, 1984 was drier during October (during pod fill) than 1985 (Table 1).

In the May 1985 planting, LAI could not be measured after the peak because of the initial leaf stunting that occurred due to pesticide injury to the initial foliage. The higher LAI of Kirby corresponds to its greater branching discussed above compared to Duocrop, but differences in LAI between the cultivars, although present, were not significant over all densities at both planting dates.

A significant cultivar x planting date x plant density interaction in LAI accumulation was observed in the May planting (Fig. 4a; Table 2).

Light interception

May and July 1985 light interception measurements for Kirby (DT) and Duocrop (INDT) were plotted against LAI and regression equations were determined, the slopes of which were negative since light

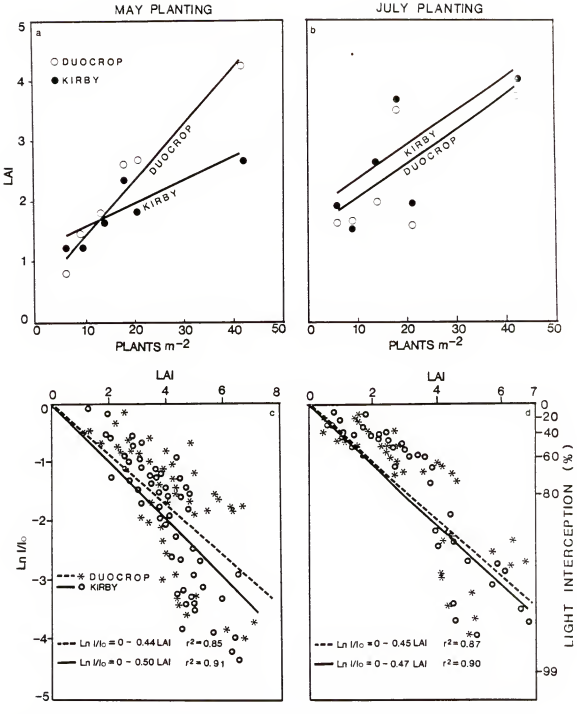

Fig. 4. Leaf area index (LAI) in Kirby (determinate) and Duocrop (indeterminate) soybean cultivars influenced by plant density (function of inter- and intra-row spacing) and planting dates (average of 1984 and 1985) (a, b). Relationship between light interception and LAI influenced by Kirby and Duocrop in May and July plantings, 1985 (c, d).

interception increased with increasing LAI. The slopes of these equations are assumed to be the extinction coefficients (K) and were calculated for each cultivar according to Beer's Law, $\ln I/Io = e^{-K(LAI)}$, where I and Io are the irradiance below and above the canopy, respectively.

Light interception (extinction) was greatest in the narrow-row widths, Kirby cv., high plant densities, and the May plantings (Fig. 4c, d; Table 4). Extinction coefficients for both Kirby and Duocrop were 0.62 for the May planting and were 0.48 and 0.54, respectively, for the July plantings. Slopes (K) for cultivars did not differ significantly from each other. Canopy closure in 30-cm rows (mean of cultivars) occurred on 51 DAP, compared to 89 DAP in the conventional (91 cm) rows. The fact that canopies in 30-cm rows intercepted more light than 91-cm rows despite the range of density, 18 to 42 plants m^{-2}, illustrates the overriding influence of square planting arrangement on light interception compared to the "hedge-row" effect present in wide (conventional) rows.

Dry Matter Production

The total, main-stem, and branch dry matter (DM) production was greatest in the Kirby (DT) cv., May planting, and high-plant densities (Fig. 5a, 6a-f; Table 2). The May planting of 1984 (Fig. 5a) was not included because of plot variability due to chemical damage that occurred from an over dosage of an insecticide. The total, main-stem, and branch DM plant $^{-1}$ at maturity decreased with increasing plant density. Production of total and main stem DM m^{-2} increased with

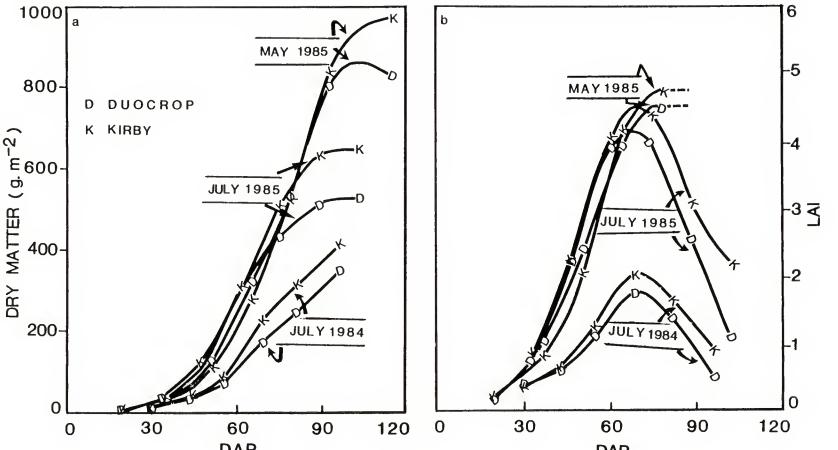

Fig. 5. Dry matter accumulation (a) and LAI (b) in Kirby (determinate) and Duocrop (indeterminate) soybean cultivars (averaged on all densities) over days after planting (DAP).

increasing plant density. However, DM production from branches decreased in the May planting with increasing density and remained almost constant in the July planting. This difference was not so apparent in the July planting, but the July plants were smaller statured than those of May planting. Differences in total and main stem DM production between cultivars was statistically significant up to 21 plants m^{-2} except for main-stem dry matter in May planting but not beyond this density.

The total dry matter production increased with the increasing squareness of planting pattern for both cultivars and planting dates ($r^2 > 0.81$) (Fig. 7c, d). A significant correlation was observed between total dry matter yield and seed yield (Table 3).

Crop Growth Rate

Crop growth rate was significantly greatest for narrow rows vs. wide and for Kirby (DT) cv. vs. Duocrop (INDT) (Table 5). For both years, planting dates, and cultivars, CGR for the 30- x 18-cm spatial arrangement was approximately double that of 91 x 8 cm (conventional), although plant density for the two arrangements was similar (18 vs. 14 plant m^{-2}, respectively). The crop growth rate for Kirby in the 30- x 8-cm pattern (42 plants m^{-2}) was significantly greater than the other 30-cm width combinations only in the May 1985 planting, again indicating that spatial arrangement had a greater effect on CGR than plant density. Across all planting dates and years the mean CGR for 30- x 18-cm (18 plants m^{-2}) and 30- x 8-cm (42 plants m^{-2}) patterns were 11.2 and 11.1, respectively.

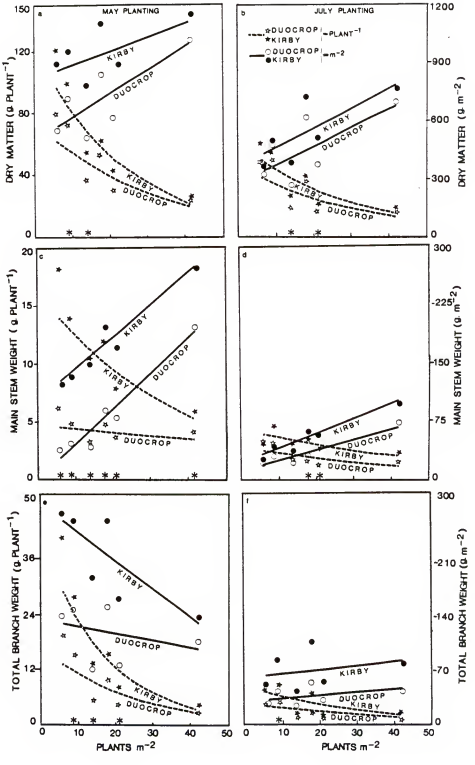

Fig. 6. Dry matter, main stem and total branch weight in Kirby (determinate) and Duocrop (indeterminate) soybean cultivars influenced by plant density (function of inter- and intra-row spacing) and planting dates (average of 1984 and 1985). *Indicates significant differences between cultivars at each level of plant density ($P < 0.05$) according to Duncan's Multiple Range Test (DMRT).

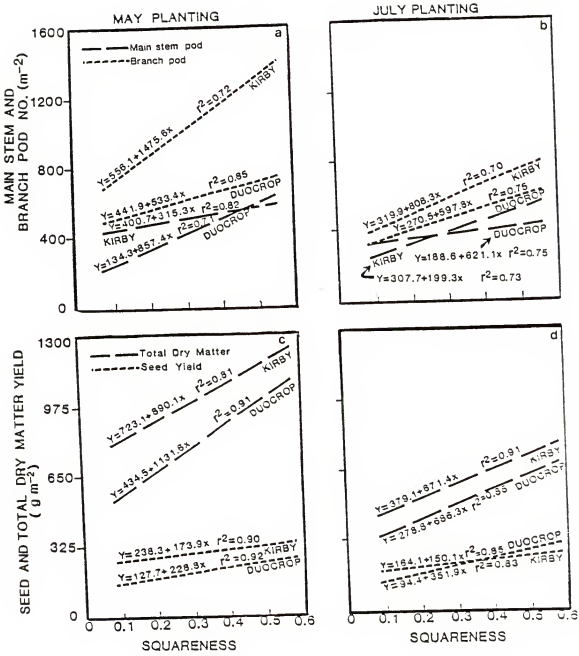

Fig. 7. Pod number on main stem and branches, seed and total dry matter yield of Kirby (determinate) and Duocrop (indeterminate) soybean cultivars influenced by squareness of planting pattern and dates (average of 1984 and 1985).

Table 4. Light extinction coefficient of Kirby (determinate) and Duocrop (indeterminate) soybean cultivars in May and July plantings, 1985.

Planting date	Cv.	Plant density (m^{-2})					
		6	9	14	18	21	42
		Inter- and intra-row spacing (cm)					
		(91x18)	(61x18)	(91x8)	(30x18)	(61x8)	(30x8)
May 1985	Kirby	0.28aD	0.39aCD	0.36aD	0.52aAB	0.48bBC	0.62aA
	Duocrop	0.30aC	0.27bC	0.33aBC	0.41aB	0.61aA	0.62aA
July 1985	Kirby	0.37aABC	0.28aC	0.33bBC	0.46aA	0.40aAB	0.48aA
	Duocrop	0.40aBC	0.27aC	0.44aAB	0.34bBC	0.34aBC	0.54aA

Means followed by the same lowercase letters in the same column and means followed by the same uppercase letters in the same row are not significantly different ($P<0.05$) according to Duncan's Multiple Range Test (DMRT).

Table 5. Crop growth rate of Kirby (determinate) and Duocrop (indeterminate) soybean cultivars in May planting, 1985 and July plantings, 1984 and 1985.

Planting date	Cv.	Plant density (m^{-2}) 6	9	14	18	21	42
		Inter- and intra-row spacing (cm)					
		(91x18)	(61x18)	(91x8)	(30x18)	(61x8)	(30x8)
		$g\ m^{-2}\ day^{-1}$					
July 1984	Kirby	4.6aB	5.6aAB	4.4aB	7.3aA	6.4aAB	7.5aAB
	Duocrop	3.1aC	5.5aB	3.3aC	4.5bBC	4.5aBC	6.4aA
May 1985	Kirby	8.9aD	11.8aC	8.1aD	14.8aB	12.1aC	16.1aA
	Duocrop	8.0aE	11.3aC	6.9bF	14.5aA	9.9bD	12.8bB
July 1985	Kirby	6.1aC	10.3aB	7.0aC	14.3aA	10.1aB	13.2aA
	Duocrop	5.5aC	8.4aB	4.7bC	12.0aA	7.6bB	10.5aA

Means followed by the same lowercase letters in the same column and means followed by the same uppercase letters in the same row are not significantly different ($P<0.05$) according to Duncan's Multiple Range Test (DMRT).

Reproductive Growth

Days to growth stages R1 and R7

In the May planting, Kirby (DT) and Duocrop (INDT) required 52 and 49 DAP, respectively, to reach R1 stage, whereas in the July planting, 40 DAP were required to reach R1 for both cultivars. Both Kirby and Duocrop reached the R7 stage at ca. 117 and 99 DAP in May and July plantings, respectively.

Pod production

The number of pods plant^{-1} on main stem and on the branches decreased exponentially with increasing density in both plantings and both cultivars (Fig. 8a, b, c, d; Table 2). Since increasing plant density affected pod number in Duocrop (INDT) more than in Kirby (DT) in July planting, a significant cultivar x planting date x plant density interaction resulted. Kirby produced more pods on the branches than Duocrop in both planting dates (Fig. 8c, d) except in the highest density in May planting indicating plant density affected branch-pod formation more in Kirby than in Duocrop in early planting. No significant differences in main-stem and branch pods between the cultivars were observed in densities greater than 21 plants m^{-2}, which indicates that the cultivars differed for pod number only in the wider inter-row spacings and in lower densities only, where Kirby had the advantage.

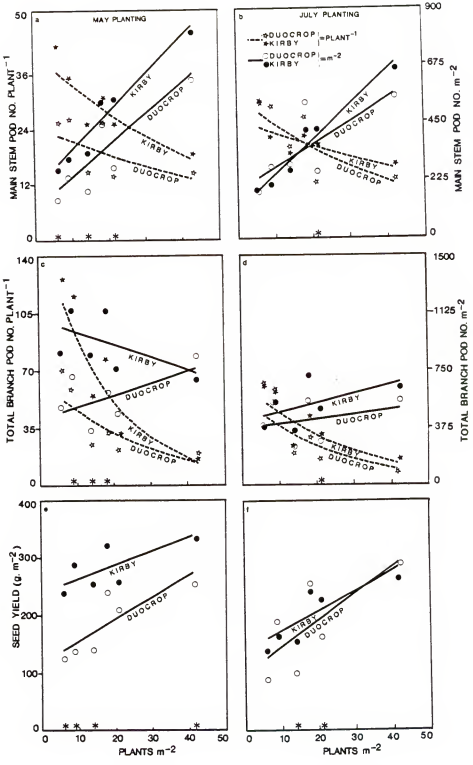

Fig. 8. Main stem and total branch pod number and seed yield in Kirby (determinate) and Duocrop (indeterminate) soybean cultivars influenced by plant density (function of inter- and intra-row spacing) and planting dates (average of 1984 and 1985).

*Indicates significant differences between cultivars at each level of plant density ($P < 0.05$) according to Duncan's Multiple Range Test (DMRT).

Branch-pod number increased sharply ($P < 0.01$) with increasing squareness of planting pattern for both cultivars, particularly with Kirby, in both the May and July plantings (Fig. 7a, b). Main-stem pod number also increased significantly with increasing squareness. However, there was a significant cultivar x squareness interaction in both planting dates due to the greater responsiveness of Duocrop than Kirby to increased squareness of planting pattern. A strong positive correlation between main stem nodes and main-stem pods was observed in both planting dates (Table 3). The correlation between branch number and branch pod number was greater in the July compared to the May planting. The correlation between branch nodes and branch pods was also significant except in the May planting, 1985 (Table 3).

Seed yield

Seed yield increased with increasing plant density for both cultivars and in both planting dates (Fig. 8e, f). The highest seed yield (341.4 g m^{-2}) was obtained from Kirby (DT) in the May and the 30- x 8-cm planting pattern. Duocrop (INDT) tended to yield more than Kirby in the July planting at higher densities and closer row spacing (Fig. 8f). The cultivar x plant density x planting date interaction was significant. Board and Hall (1985) reported that yield losses from nonoptimal planting date resulted from reduced branch number, which caused a reduction in branch yield. The branch number in this experiment was reduced in July planting compared to May. However, yield losses can be reduced by increasing branch number per area by planting in narrow rows with higher densities. These data indicate

that Duocrop may have an advantage over Kirby in July planting in narrow rows and high density. In fact, the highest seed yield (289.5 g m^{-2}) in the July planting was from Duocrop in the close-row spacing and highest density (Fig. 9).

The square pattern effect was observed for seed yield (Fig. 7c, d). Seed yield was greater in the more nearly square pattern compared to the less square even though the plant densities were similar. Seed yield increased in both cultivars with increasing squareness of planting pattern although Duocrop responded more than Kirby, but significantly so only in the July planting, which resulted in a significant cultivar x squareness interaction. However, the relationship between yield and squareness was highly significant ($r^2 >$ 0.83) for both cultivars. Seed yield, total dry matter, nodes and pods and branches was positive and generally significantly correlated with squareness of planting pattern (Table 3). Considering that seed yield responded to both plant density and planting pattern squareness, it was apparent that plant density and planting pattern were partially confounded in their effect on seed yield. In order to attempt to analyze for the independent effects of plant density and squareness on seed yield, yield data was analyzed by three different models.

First, a stepwise regression analysis was done by using the following quadratic model:

Seed yield = PD PD*PD SQ SQ*SQ PD*SQ PDT CUL (1)

where PD = plant density, SQ = squareness of planting pattern, PDT = planting date, and CUL = cultivar. Two models from stepwise regression were considered as follows:

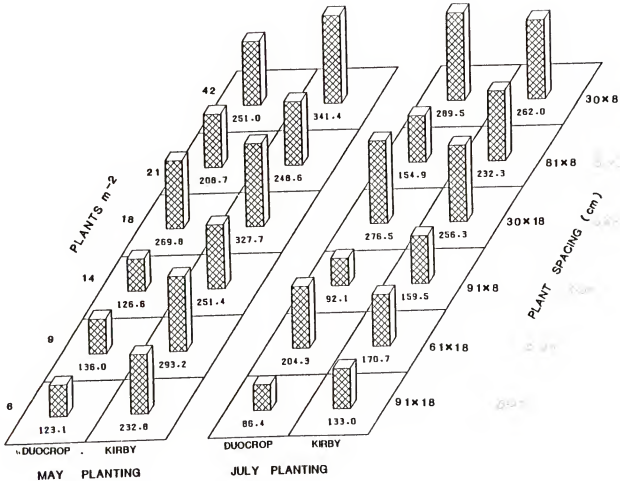

Fig. 9. Seed yield in Kirby (determinate) and Duocrop (indeterminate) soybean cultivars influenced by plant density, spacing and planting dates (average of 1984 and 1985). Number in each square is seed yield in g m^{-2}.

$$\text{Seed Yield} = 143.44 + 9.42\ (PD) + 650.01\ (SQ) - 25.22\ (PD*SQ) - 41.07(PDT) - 57.51 \quad (2)$$

$$\text{Seed Yield} = 245.30 + 3.37\ (PD) + 214.03\ (SQ) - 41.07\ (PDT) - 57.51\ (CUL) \quad (3)$$

Since the interaction term (PD*SQ) in eqn. (2) appeared to be non-significant, eqn. (3) was therefore considered as the best linear model. All the variables in this model (eqn. 3) were highly significant ($P < 0.001$). From the model it was evident that the change in yield due to plant density ranged from 6 to 42 plants m^{-2} was 121.32 g m^{-2} and due to squareness ranged from 0.09 to 0.60 was 109.15 g m^{-2}. Later planting date (July = 2) and cultivar (Duocrop = 2) had a negative effect.

The effect of inter-row spacing alone on seed yield was regressed (linear model) against plant density (Fig. 10a, b). Kirby seed yields were greater than Duocrop in all the inter-row spacings and in both planting dates. The 30-cm inter-row spacing resulted in the greatest yield over both cultivars in both planting dates, particularly at the density of 18 plants m^{-2} (30 x 18-cm spacing), which squareness was 0.60. According to these observations, seed yield for both determinate and indeterminate soybean cultivars can be optimized by using narrow rows to achieve more square arrangement with plant density of 18 to 42 plants m^{-2}.

Non-linear regression analysis was also made to compare seed yield at each planting pattern squareness with the plant density by combining cultivars, planting dates, plant density and squareness. The following model for soybean seed yield was fitted to these data:

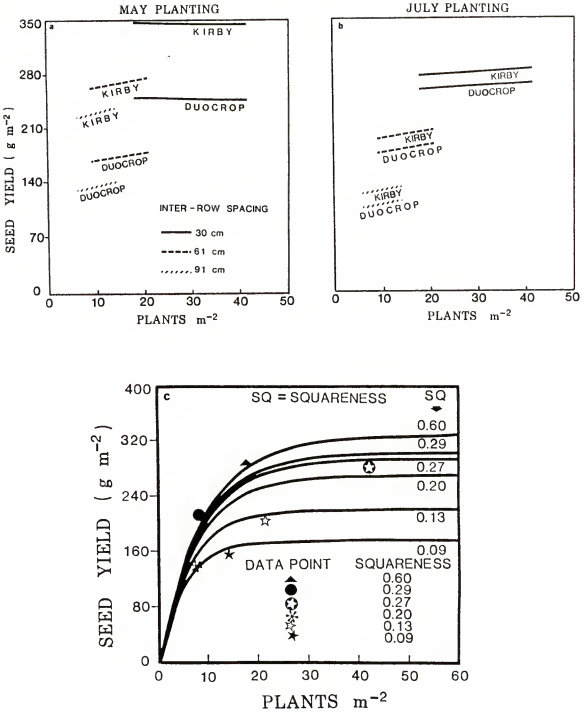

Fig. 10. Seed yield of Kirby (determinate) and Duocrop (indeterminate) soybean cultivars at each inter-row spacing, plant density and planting dates (average of 1984 and 1985) (a, b). Seed yield of Kirby (determinate) and Duocrop (indeterminate) soybean cultivars at each squareness of planting pattern and plant density (average of cultivars and planting dates of 1984 and 1985) (c).

$$\text{Seed Yield} = \text{MAX} * (1- \text{Exp}(-\text{ISQ}*\text{SQ}/\text{MAX})) * (1- \text{Exp}(- \text{IPD} * \text{PD}/\text{MAX} * (1- \text{Exp}(-\text{ISQ} * \text{SQ}/\text{MAX})))) \quad (4)$$

where MAX = maximum seed yield at maximum plant density and squareness = 1.0, ISQ = initial slope of seed yield versus squareness when plant density is maximum, and IPD = initial slope of seed yield versus plant density when squareness is maximum (1.0). The model appeared to successfully separate out the effects of plant density and squareness. Solved coefficients were MAX = 329.09 g m^{-2}, ISQ = 36.00, and IPD = 2787.57. The model suggested a linear response to plant density at very low densities (less than 5 plants m^{-2}) irrespective of squareness (Fig. 10c). However, as squareness was increased, the response to density also increased. Seed yield tended to optimize as plant density exceeded 18 plants m^{-2} at each of the squareness values of 0.27, 0.29, and 0.60. This indicates again that seed yield of both determinate and indeterminate soybean cultivars can be optimized at a plant density of between 18 to 42 plants m^{-2} and at a squareness approaching 1.0 at either optimum or later seeding dates.

CHAPTER IV
GENERAL SUMMARY AND CONCLUSION

Numerous studies have shown that soybean seed yields increase with increasing canopy density, particularly when associated with narrow-row planting patterns. Indeterminate cultivars, in particular, which are grown mostly in the northern states, responded positively to narrow rows. However, other studies demonstrated that determinate cultivars, which are predominately grown in the south, often did not respond to narrow-row arrangements.

Few studies have included both determinate and indeterminate cultivars of similar maturity grown under the same environmental condition, for comparing vegetative and reproductive behavior in varying canopy structure. Therefore, field experiments were carried out using two planting dates, May and July, in 1984 and 1985 to assess the vegetative and reproductive responses of determinate and indeterminate soybean cultivars to canopy structure resulting from varying spatial arrangements (inter- and intra-row spacings).

Two cultivars Kirby (DT, MG VIII) and Duocrop (INDT, MG VII), two planting dates, May and July, three inter-row spacings of 91, 61, and 30 cm, and two intra-row spacings of 8 and 18 cm were used. These resulted in plant densities of 6, 9, 14, 18, 21, and 42 plants m^{-2}. Plots were sampled for growth analysis at 2-week intervals beginning 20 DAP until 120 DAP and 96 DAP for the May and July plantings,

respectively, in 1984 and 1985. Plant component analysis was done from a representative subsample and the following measurements were recorded: plant height, branch number and total branch length, LAI, CGR, node and pod number on the main stem and branches, and seed and dry matter yields and expressed on a $plant^{-1}$ and m^{-2} basis. The May and July planting dates in 1985 were used to determine light interception.

Plant height, total branch length and node number on main stem and branches in the indeterminate Duocrop was greatest compared to the determinate Kirby in both planting dates and years. Nodes number on the main stem and on the branches decreased $plant^{-1}$ and increased m^{-2} with the increasing plant density. The determinate cultivar produced more branches than the indeterminate cultivar in May planting across all densities. In July planting, significant cultivar x planting date x plant density interaction for total branch numbers resulted from more branches in the determinate cultivar in the closer spacing and comparatively higher plant densities.

Leaf area index (LAI) and crop growth rate (CGR) was higher for determinate than for the indeterminate cultivar on both planting dates and increased with increasing plant density. The determinate cultivar intercepted more light than the indeterminate and had a higher coefficient of light extinction. These results indicate a favorable advantage for the determinate cultivar, however, both cultivars responded to increasing plant density.

Number of pods on the main stem and on the branches and the total, stem, branch and seed dry matter production was greatest in the

determinate cultivar compared to the indeterminate cultivar across all densities, years, and planting dates. Dry matter production increased m^{-2} and decreased $plant^{-1}$ with increasing plant density except for the total branch dry matter, which decreased m^{-2} in May planting with increasing density. Short, thin branches produced in close densities resulted in lesser total branch dry weight. Significant cultivar x planting date x plant density interaction resulted in the indeterminate cultivar producing more pods on the main stem in wider spacings and higher seed yield in closer spacings in the July planting. Generally, pod numbers increased m^{-2} and decreased $plant^{-1}$ with increasing densities.

The squareness of planting pattern effect influenced both determinate and indeterminate cultivars to produce greater LAI, light interception, CGR, node and pod number, total and seed dry matter yield, while tending to reduce plant height. Larger but not taller plants showed mitigate against lodging, although lodging was not observed in any of the planting patterns in this study.

It is concluded that soybean seed yield can be optimized by plant density between 18 to 42 plant m^{-2} in close-row spacing, approximating a square planting arrangement for both determinate and indeterminate cultivars, whether planted at an optimum (May) or late seeding date (July). Therefore, the initial hypothesis that the determinate and indeterminate soybean cultivars respond differently to canopy structure as produced by plant density, planting pattern and date is rejected.

APPENDIX

Table 6. Treatment combinations used in soybean spatial arrangment experiment in 1984 and 1985.

Treatment	Cultivar	Inter-row spacings	Intra-row spacings	Plant density
		cm	cm	plants m^{-2}
1	Kirby	91	18	6
2	Duocrop	91	18	6
3	Kirby	91	8	14
4	Duocrop	91	8	14
5	Kirby	61	18	9
6	Duocrop	61	18	9
7	Kirby	61	8	21
8	Duocrop	61	8	21
9	Kirby	30	18	18
10	Duocrop	30	18	18
11	Kirby	30	8	42
12	Duocrop	30	8	42

Kirby--Determinate growth type.

Duocrop--Indeterminate growth type.

Table 7. Seed yield of Kirby (determinate) and Duocrop (indeterminate) soybean cultivars as influenced by spacing, plant density and squareness of planting pattern in May and July plantings (mean of 1984 and 1985).

Row spacing Inter	Row spacing Intra	Plant density	Pattern squareness	May Kirby	May Duocrop	July Kirby	July Duocrop	Mean
cm	cm	plants m^{-2}		g m^{-2}				
30	8	42	0.27	341.4a	251.0ab	262.0a	289.5a	286.0
30	18	18	0.60	327.7ab	269.8a	256.3a	276.5a	282.6
61	8	21	0.13	248.6ab	208.7b	232.3ab	154.9b	211.1
61	18	9	0.29	293.2ab	136.0c	170.7bc	204.3ab	201.0
91	8	14	0.09	251.4ab	126.6c	159.5bc	92.1b	157.4
91	18	6	0.30	232.8b	123.1c	133.0c	86.4b	143.8
Mean				282.5	185.8	202.3	183.9	

Means followed by the same letters in the same column are not significantly different ($P<0.05$) according to Duncan's Multiple Range Test (DMRT).

Table 8. Seed yield of Kirby (determinate) and Duocrop (indeterminate) soybean cultivars within inter-row (average of intra-rows) and intra-row (average of inter-rows) spacing in May and July plantings (mean of 1984 and 1985).

Spacing	May		July	
	Kirby	Duocrop	Kirby	Duocrop
cm	g m^{-2}			
	Inter-row spacing			
30	334.6a	260.5a	259.2a	283.0a
61	271.0ab	172.4b	201.6b	179.7b
91	242.2b	124.9c	146.3b	89.3c
	Intra-row spacing			
8	280.5a	195.5a	218.0a	178.9a
18	284.6a	176.4a	186.7a	189.1a

Means followed by the same letters in the same column are not significantly different ($P<0.05$), according to Duncan's Multiple Range Test (DMRT).

Table 9. Harvest index of Kirby (determinate) and Duocrop (indeterminate) soybean cultivars influenced by plant spacing and density in May and July plantings (mean of 1984 and 1985).

Plant spacing	Plant density	May		July	
		Determinate Kirby	Indeterminate Duocrop	Determinate Kirby	Indeterminate Duocrop
cm	plants m^{-2}	%			
91 x 18	6	31a	24ab	34b	29a
61 x 18	9	31a	29b	34b	43a
91 x 8	14	36a	34ab	42ab	36a
30 x 18	18	30a	31ab	33b	42a
61 x 8	21	35a	39a	46a	43a
30 x 8	42	30a	26ab	35b	41a

Means followed by the same letters in the same column are not significantly different ($P<0.05$) according to Duncan's Multiple Range Test (DMRT).

Table 10. Harvest index of Kirby (determinate) and Duocrop (indeterminate) soybean cultivars within inter-row (average of intra-rows) and intra-row (average of inter-rows) spacings in May and July plantings (mean of 1984 and 1985).

	May		July	
Spacing	Determinate Kirby	Indeterminate Duocrop	Determinate Kirby	Indeterminate Duocrop
cm	%			
Inter-row spacing				
30	30a	29a	34a	42ab
61	33a	29a	40a	43a
91	34a	29a	39a	32b
Intra-row spacing				
8	34a	33a	41a	39a
18	31a	25a	34b	38a

Means followed by the same letters in the same column are not significantly different ($P<0.05$), according to Duncan's Multiple Range Test (DMRT).

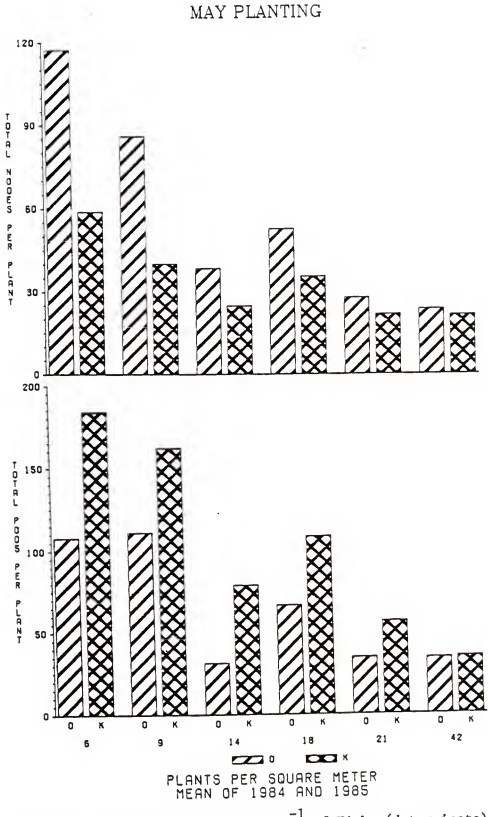

Fig. 11. Total node and pod number plant^{-1} of Kirby (determinate) and Duocrop (indeterminate) soybean cultivars in May planting (D = Duocrop, K = Kirby).

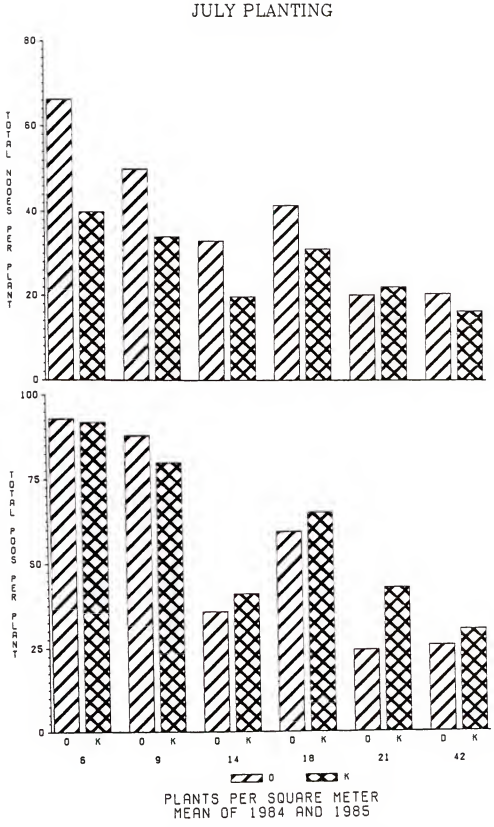

Fig. 12. Total node and pod numbers plant^{-1} of Kirby (determinate) and Duocrop (indeterminate) soybean cultivars in July planting (D = Duocrop, K = Kirby).

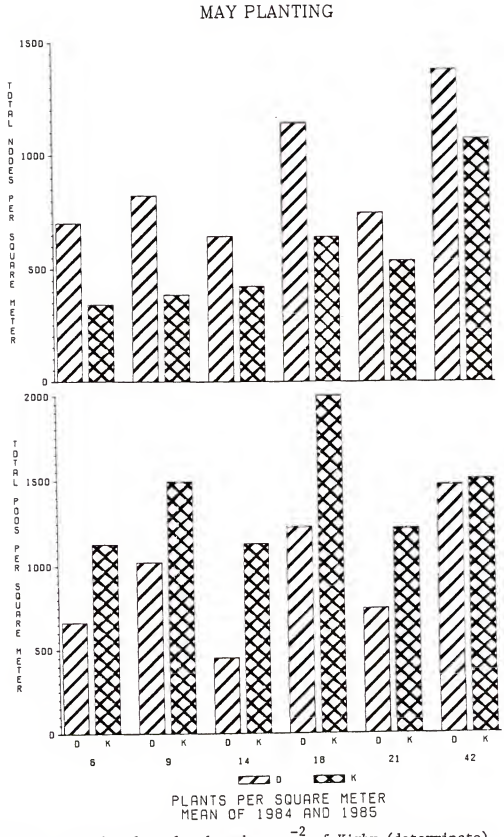

Fig. 13. Total node and pod numbers m^{-2} of Kirby (determinate) and Duocrop (indeterminate) soybean cultivars in May planting (D = Duocrop, K = Kirby).

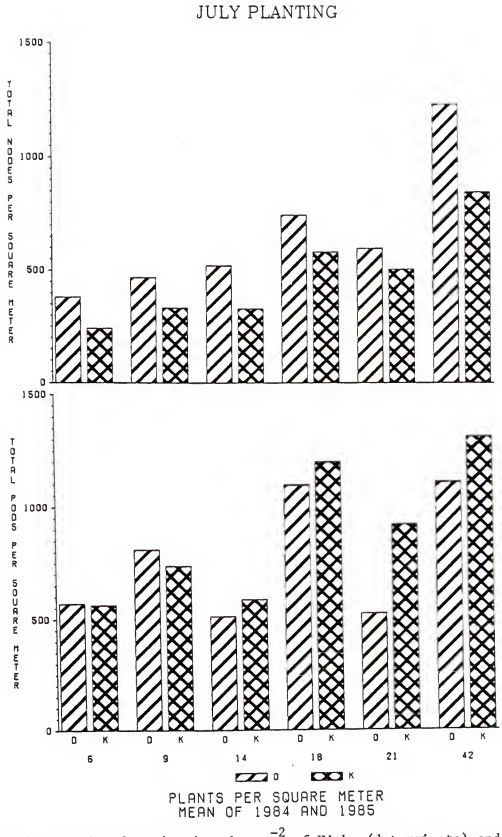

Fig. 14. Total node and pod number m^{-2} of Kirby (determinate) and Duocrop (indeterminate) soybean cultivars in July planting (D = Duocrop, K = Kirby).

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BIOGRAPHICAL SKETCH

M. A. Qaiyum Parvez was born on June 28, 1953, in Lalmonirhat, Bangladesh. He attended primary school, secondary school, and college in P.T.I., Zilla School, and Govt. M. M. College, respectively, in Jessore, Bangladesh. In 1970, he was admitted to the Bangladesh Agricultural University, Mymensingh, to study agriculture, and graduated with an honors degree in 1975.

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Parvez joined the Bangladesh Rice Research Institute (BRRI) as scientific officer in 1977 and was promoted to senior scientific officer in January 1983. He enrolled in the University of Florida at Gainesville for his Ph.D. degree in fall 1983.

Parvez is a member of the American Society of Agronomy, the Crop Science Society of America, as well as Gamma Sigma Delta Honor Society. He is an IRRI alumni and also a member of Bangladesh Krishibid Somity, and Bangladesh Society for Advancement of Science.

He is married and has a son and a daughter.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Dr. F. P. Gardner, Chairman
Professor of Agronomy

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Dr. K. J. Boote
Professor of Agronomy

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